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Citation for published version:
Wang, Y & Rush, D 2018, 'Determination of critical fallout condition of tempered glass in an enclosure fire', *Fire Safety Journal*, vol. 101, pp. 18-24. https://doi.org/10.1016/j.firesaf.2018.08.010

Digital Object Identifier (DOI):
10.1016/j.firesaf.2018.08.010

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Fire Safety Journal

Determination of critical fallout condition of tempered glass in an enclosure fire

Yu Wang*, David Rush

School of Engineering, BRE Centre for Fire Safety Engineering, University of Edinburgh, Edinburgh EH9 3JL, United Kingdom

Nomenclature

f Probability density function

F Failure probability function

q Heat flux (kW/m^2)

S Survival probability function

t Time (s)

T Temperature (°C)

Greek

β Shape parameter

η Scale parameter

γ Location parameter

Δ Difference

Subscripts

1-5 Thermocouple number

cf Clear float

cc Clear coated

* Corresponding Author: E-mail: Yu.Wang@ed.ac.uk (Y. Wang)

Abstract

Tempered glass is extensively used in modern high-rise buildings. However, in some instances the glass will break and fall out when subjected to a fire which will create a new ventilation condition, drastically changing the enclosure fire dynamics. In this work, eleven tempered glass panels with dimensions of 815×815×6 mm^3 were heated by a pool fire placed in the center of a 1000×1000×1000 mm^3 compartment. Parameters such as glass surface temperature, heat flux, failure time and fallout behavior, were all recorded. Weibull distributions were then employed to investigate the probabilistic characteristics of tempered glass fallout. Failure probability functions, survival probability functions, and probability density functions (derivative of failure probability function) of tempered glazing were obtained and compared with those of clear and coated glazing. The critical temperature difference and critical heat flux, with 5% failure possibility for 6 mm-thick tempered glazing, are 301 °C and 36.17 kW/m^2, respectively, which could be used as a conservative estimate for the safe design of glass façades in a fire.

Keywords: tempered glass; fallout; Weibull distribution; failure probability

1. Introduction

Glass façades are increasingly used in modern construction for both their architectural and energy saving with its technology development in recent years [1]. However, the glass is prone to breakage and fallout when exposed to fire, creating new openings, increasing the air entrainment and external fire spread potential, and significantly changing the compartment fire development and dynamics. Emmons first highlighted this issue as an important structural problem [2], and subsequently a large number of studies have been conducted to investigate the glass breakage mechanism. For example, Keski-Rahkonen theoretically determined the breakage condition of float glass in a fire and indicated that exceeding thermal stresses within the glass is the critical reason for crack initiation [3]. Pagni et al. developed a simple model, called BREAK1, to predict the window glass breakage time in a compartment fire [4]. Shields et al. performed full-scale tests in ISO 9705 room to study the breakage and fallout behavior of double glazing [5]. Wang et al. developed finite element method (FEM) software EASY to predict the stress distribution and crack path in glazing [6].

However, almost all the previous work focused on the float glass that is normally used in ordinary windows [7]. With developments within construction, glass technology and architectural aesthetic, tempered glass is more frequently being used instead of float glass, especially in high-rise building glass façades, due to its good thermal resistance and mechanical performance [7, 8]. It is anticipated that the thermal behavior of tempered glass is very different from float glazing and the limited knowledge about it will inevitably bring potential fire risk and uncertainty during the fire performance-based design [9]. Thus, it is becoming necessary to investigate the breakage and fallout behavior of tempered glass.

Manzello et al. [10] conducted a real scale compartment fire to investigate the behavior of single and double-pane tempered glass. Klassen et al. [11] tested seven different tempered glazing samples. Nevertheless, no repeated tests were performed. To the authors' knowledge, there is no research that systematically determines the critical breakage condition of tempered glass in fire, especially its probabilistic failure characteristics [7, 10, 12]. In the present work, eleven identical experiments were repeated in a model fire compartment and the Weibull distribution was employed to deepen the understanding of its crack probability of a glass bearing certain temperature and heat flux. The specific details of experimental results and analysis are shown in the following sections.

2. Experimental setup and theoretical principles

A total of eleven tempered glass panels, with a dimension of 815×815×6 mm^3, were installed in the front wall of a 1000×1000×1000 mm^3 compartment, as shown in Fig. 1(a). The walls of this enclosure were constructed of 5 mm stainless steel lined with 20 mm-thick plasterboards. The glass panel was placed vertically in the square groove which is slightly larger than the dimension of glass (815×815 mm^2). Then the metal frame was placed on the glass and fixed by the four screws at corners, as shown in Fig. 1(a). A gasket, namely 5 mm thick ceramic fibre blanket, was inserted between the glass and frame to simulate the insulation condition. Thus, there is no constraint from the frame perimeter, but only the constraint in the thickness direction. The pressure in the thickness direction was not measured but the screw was marked during each installation process to make sure the pressure in all tests was identical. The width of covered areas was 20 mm. The glass pane edges were polished. The physical properties of these samples were not measured, but its corresponding float glass (the same raw materials) properties were measured by the authors: the elasticity modulus is 67.21 GPa; linear expansion coefficient is 8.46×10^{-6} [13]. These two parameters are always considered identical to float one. The ultimate stress of tempered glazing is 4-5 times of float [14] which should be in the range of 143-179 MPa as per float glass 35.72 MPa [13]. A 200×200 mm^2 square heptane pool fire was placed at the center of the compartment, and a ventilation opening of 200×1000 mm^2 was incorporated into the back wall of the compartment to ensure the continuous burning. In each test, the fuel of

1800 mL kept burning for more than 400 s so that the glass panel would fail before the fire extinction.

Five K-type sheet thermocouples (TC), with a measurement range of 0-1200 °C and sensitivity of 41 μV/°C, were attached on the glass surface using highly thermal conductive adhesives. Among the five thermocouples, four were attached to the covered area and not affected by the flame radiation. The temperatures measured in the covered area are considered relatively accurate. The central sheet TC was covered by high-temperature resistance tape to avoid radiation. What is more, the sheet thermocouples increased the contact area between the glass and thermocouple which ensure the reasonable measurement. Thus, the uncertainty of TCs for glass temperature measurement was estimated at 10-20% under fire condition [15]. A water-cooled total heat flux (HF) gauge with a measurement range of 0-100 kW/m^2 was placed flush to the glass surface to measure the incident heat flux. The responsivity of the gauge is 0.0906 mV/(kW/m^2) and the uncertainty in a fire environment was ±8-14% [8]. A data acquisition system with 16 channels for thermocouples and heat flux gauge was used with the sampling frequency of 1.0 Hz. The distribution of thermocouples and heat flux is shown in Fig. 1(b).

Due to the uncertainties involved in glass physical properties, a probabilistic rather than a deterministic approach is needed to determine the critical fallout condition of tempered glass in the fire. The cumulative Weibull function was employed to describe the distribution of the measured parameters. The three-parameter Weibull function is [4, 16]:

$$F(\mathrm{x}) = 1 - \exp\left[-\left(\frac{x-\gamma}{\eta} \right)^{\beta} \right] \qquad x \geq \gamma \tag{1}$$

with η, β and γ being the scale, shape and location parameters, respectively. If γ=0, the distribution becomes the two-parameter Weibull distribution. The failure probability, survival probability, probability density functions are determined according to the experimental results. The failure probability function is the general form of the cumulative Weibull distribution function and in this work the failure probability increase from 0 to 1 when the time, central temperature, temperature difference and heat flux increase. The survival probability is equal to unity minus the failure probability. The probability density function is the derivative of the failure probability which will be used to specify the probability of the random variable falling within a particular range of values.

3. Results and discussion

According to the Law of Large Numbers, the more repeated tests, the closer the results reach the true value. Thus, all the tests were conducted under the strictly controlled identical conditions. Considering the experimental expense and difficulty, 11 tests were finally repeated. Once the internal thermal stresses exceed the glass's tensile strength, a crack will be initiated. From experiments, it was found that, for tempered glass, the crack initiation and glass panel fallout process occurred at almost the same time. When a crack initiates, the energy stored in in glazing by the tempering process [12] now has a path through which to dissipate and thus the fallout of the panes is complete and almost instantaneous with crack initiation. The failure process in each test was completed within 1 s and all the panels broke into a large number of small pieces with a fallout fraction of 100%, as shown in Fig. 2. This phenomenon is very different from float glazing, which is prone to falling out gradually with a significantly smaller fallout fraction (~20%) [17, 18].

The fallout time, temperature at the center of the glass pane (T_1), temperature difference and total heat flux at the time of fallout occurrence were summarized in Table 1. It should be noted that the temperature difference is defined as:

$$\Delta T = T_1 - \frac{T_2 + T_3 + T_4 + T_5}{4} \tag{2}$$

where ΔT is the temperature difference; T_x is the temperature measured by TC_x. It was established that all the fallout occurred in the post-flashover phase at the time 333-399 s. The average critical central temperature, temperature difference and heat flux are 539 °C (standard deviation 24 °C), 357 °C (standard deviation 25 °C) and 53.1 kW/m^2 (standard deviation 11.0 kW/m^2), respectively. It should be noted that the authors have previously used the uniform radiation panel to heat float glass, its breakage temperature was also found to vary from 143-193 °C [19].

The primary reason for the difference in results between the eleven repeated tests is the physical condition of the glass: tiny flaws random distribute in the glass pane which causes the scholastic characteristic of glass breakage. Even though the glass was tested in ambient conditions at bench scale, its strengths varied greatly from 36.8-128 MPa [20]. Using the pool fire in the compartment may cause additional errors due to the fluctuation of flame and air entrainment. Thus, the measured heat flux has relatively large standard deviation than our previous tests in open space, but the temperature measurement is much more stable and reasonable. The open space fire and the electric radiation panel cannot provide enough thermal shock to make the tempered glass break. Therefore, the variation in results, due to the physical conditions of the glass and the necessary use of a more intense but less controlled fire, are unavoidable.

Table 1. The summary of important parameters at the time of fallout.

Test No.	Fallout Time (s)	T_1 (°C)	Temperature difference (°C)	Total HF (kW/m^2)
1	348	557	382	47.0
2	361	569	365	66.0
3	377	511	351	57.3
4	399	574	368	68.0
5	358	565	381	44.7
6	333	531	325	37.1
7	370	521	350	64.6
8	365	544	361	57.9
9	339	522	379	43.7
10	343	530	300	--
11	369	510	369	44.8

Previous work of a similar nature on float glass established that the corresponding parameters average critical central temperature, temperature difference and heat flux are 152 °C (standard deviation 36 °C), 94 °C (standard deviation 2 °C) and 14.1 kW/m^2 (standard deviation 1.2 kW/m^2) [21], respectively. These are almost quarter of that determined for the tempered glazing, meaning that tempered glazing has a higher tolerance for temperatures and heat fluxes before crack initiation and glass fallout failures occur.

4. Failure, survivability and probability density functions

The failure probability function, *F(t)*, the survival probability function, *S(t)*, and the probability density function, *f(t)*, for the tempered glazing can be described using both the two-parameter and three-parameter Weibull functions. The values of R^2, β, η, and γ (for the two- and three-parameter functions) are obtained by fitting the experimental data and presented in Table 2. It can be seen that the three-parameter Weibull functions with higher R^2 values are more accurate in representing the experimental data.

Table 2. The summary of R^2, β, η and γ.

Glass critical parameter	Two-parameter			Three-parameter			
	R^2	β	η	R^2	β	η	γ
Fallout Time	0.958	22.46	368.28	0.992	1.74	40.72	324.84
T_1	0.942	27.57	549.41	0.977	1.50	44.39	500.80
Temp. difference	0.965	15.79	368.62	0.972	1357.74	31319.52	-30950.00
Total HF	0.958	5.57	57.22	0.971	1.88	25.70	30.89

Thus, in the present work, the three-parameter distributions are selected to provide the predictive functions. The time-dependent failure probability, survival probability and probability density functions for *Fallout Time* are as follows:

$$F(t) = 1 - \exp\left[-\left(\frac{t-324.84}{40.72}\right)^{1.74}\right] \tag{3}$$

$$S(t) = 1 - F(t) = \exp\left[-\left(\frac{t-324.84}{40.72}\right)^{1.74}\right] \tag{4}$$

$$f(t) = \frac{1.74}{40.72}\left(\frac{t-324.84}{40.72}\right)^{0.74} \exp\left[-\left(\frac{t-324.84}{40.72}\right)^{1.74}\right] \tag{5}$$

where t is the time in seconds. The functions are plotted in Fig. 3(a), which indicates that the glass fallout time can satisfy the Weibull function very well. The statistic variations of fallout time may be due to the variability of glass tensile strength [19, 20] due to the random distribution of tiny flaws on the glass surface, which is particularly important around the supported edges of the pane [18]. Thus, even though the thermal loading is ideally identical, the fallout time will vary between different tests. It should be noted that as the temperature development depends on the rate of heat release and the time history of fire temperature, the functions about the fallout time are only applicable in this experimental condition.

For the central glass pane temperature, temperature difference and heat flux, the failure probability functions are respectively:

$$F(T_1) = 1 - \exp\left[-\left(\frac{T_1 - 500.80}{44.39} \right)^{1.50} \right] \tag{6}$$

$$F(\Delta T) = 1 - \exp\left[-\left(\frac{\Delta T + 30950.00}{31319.52} \right)^{1357.74} \right] \tag{7}$$

$$F(q) = 1 - \exp\left[-\left(\frac{q - 30.89}{25.70} \right)^{1.88} \right] \tag{8}$$

Their curves are shown in Fig. 3(b). It can be seen that the data are in good agreement with the Weibull function as shown also in Table 2 with values approaching unity for the R^2 values. In the function of temperature difference (Eq. (7)), the location parameter, γ, is negative. This often occurs in the three-parameter Weibull distribution analysis, in which case the location parameter should be assumed to be zero and the two-parameter distribution should be used, to avoid negative critical failure parameters [22]. Thus the two-parameter Weibull distribution is drawn out to make a comparison, which is found almost identical to the three-parameter one.

Temperature difference and heat fluxes are considered the most important parameters for determining glass crack initiation [18, 21]. Although sometimes the heat flux does not directly determine the glass fallout, the researcher often employs heat flux value as it is easier to predict incident heat flux than temperature difference in a compartment fire theoretical or numerical model [5, 17, 23]. Thus, the critical incident heat flux is also very important to know for further model development. Using these two parameters, a fire resistance comparison between clear tempered, clear float and coated float glass is now presented. The experimental data of 20 repeated clear float glass and 8 coated float glass with 6 mm thickness are extracted from previous work [19, 24]. The three-parameter Weibull failure probability functions of temperature difference for clear float, ΔT_{cf}, and coated glass, ΔT_{cc}, and heat flux for clear float glass, q_{cf}, with fitness of 0.995, 0.957 and 0.983, respectively, are as follows:

$$F(\Delta T_{\mathrm{cf}}) = 1 - \exp\left[-\left(\frac{\Delta T_{\mathrm{cf}} - 98.33}{21.14} \right)^{7.91} \right] \tag{9}$$

$$F(\Delta T_{\mathrm{cc}}) = 1 - \exp\left[-\left(\frac{\Delta T_{\mathrm{cc}} + 6269.75}{6386.33} \right)^{595.10} \right] \tag{10}$$

$$F(q_{\mathrm{cf}}) = 1 - \exp\left[-\left(\frac{q_{\mathrm{cf}} + 91.69}{104.66} \right)^{34.89} \right] \tag{11}$$

It should be noted that in the clear float glazing tests, heat flux was not measured.

The comparison curve is shown in Fig 4. It can be seen that the tempered glazing can withstand much higher temperature differences and heat fluxes compared to the float glass; clear float glass can also withstand slightly higher temperature difference than coated float glass which includes a lot of surface flaws by coating process [13]. With respect to heat flux, the data suggests that there is a much greater range of failure fluxes for tempered glass than for float glass. It may be caused by the experimental condition: the pool fire and smoke in simulated compartment fluctuate significantly in the present work, but may keep relatively stable in an open space in the previous work [21]. However, this will be investigated further in future research to understand whether this is due to variation of material, experimental set-up or measurement.

To provide references to engineering, the specific temperature differences and heat fluxes at 5%, 50% and 95% failure possibility are listed in Table 3. The conservative estimates (i.e. the 5%ile estimation) for critical temperature difference and heat flux for tempered glazing are respectively 301 °C and 36.17 kW/m^2. These conservative estimations are well above the 95%ile values for clear float and coated float glasses, and show that tempered glass will, with a high level of reliability, provide better ability to resist temperatures and heat fluxes from enclosure fires.

Table 3. The corresponding temperature differences at different failure possibility.

Glass type	5%		50%		95%	
	Temperature difference (°C)	Heat flux (kW/m^2)	Temperature difference (°C)	Heat flux (kW/m^2)	Temperature difference (°C)	Heat flux (kW/m^2)
Clear tempered	301	36.17	361 °C	52.03	395 °C	77.00
Clear float	89	--	115 °C	--	134 °C	--
Coated float	58	4.43	86 °C	11.88	101 °C	16.32

5. Conclusions

In this work, a total of eleven tempered glass panels were heated till failure, represented by crack initiation and fallout under a simulated compartment fire condition. Parameters, such as heat flux, time and temperatures of the glass, were recorded to develop a failure possibility analysis using a three-parameter cumulative Weibull function. The primary conclusions are as follows:

1) Tempered glazing fails in a more catastrophic and rapid manner compared to float glass, where, once crack initiation occurs, the tempered glazing completely fell out within 1 s.

2) The critical average fallout temperature difference and heat flux of tempered glazing are approximately four times larger than those found for float glass recorded at 357 °C and 53.1 kW/m^2, respectively.
3) Three-parameter Weibull distribution can describe the statistic characteristic of tempered glass fallout better than two-parameter distribution. However, the negative location parameter in some cases should be noted and studied further.
4) Clear tempered glass can withstand higher temperatures and heat fluxes before failure compared to float glass. The fire resistance difference between tempered and float glass become larger if coated float glass is employed.
5) Failure probability, survival probability and probability density functions for tempered glazing are determined. The critical temperature difference and heat flux with a 5% failure probability for 6 mm-thick tempered glass are 301 °C and 36.17 kW/m^2, respectively, which can be suggested as the conservative value in fire safety design of glass façades.

Acknowledgements

This work is financially supported by IRIS-Fire project of UK (Engineering and Physical Sciences Research Council Grant no.: EP/P029582/1).

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Figure captions:

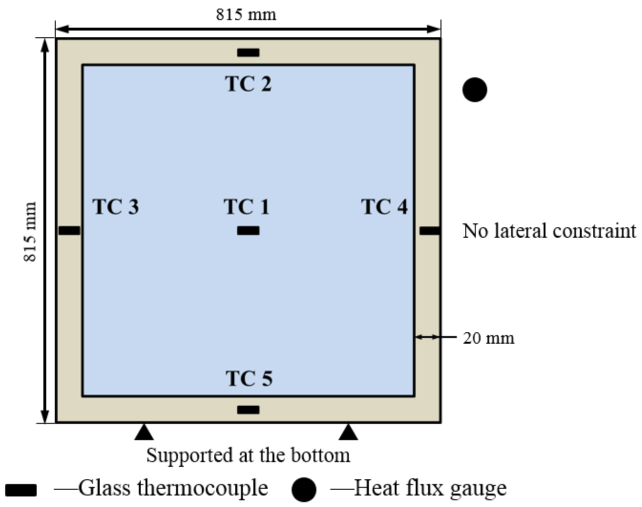
Fig. 1. The experimental setup and measurement instrument distribution. (a) The compartment model; (b) Distribution of TC and HF on fire-exposed surface.

Fig. 2. The fallout behavior in Test 4. (a) The breakage and fallout process of tempered glazing: (i) Crack initiation, 0.00 s; (ii) Glass falling out, 0.10 s; (iii) Complete fallout, 0.72 s; (b) The post crack path of tempered glazing.

Fig. 3. The curves of three-parameter Weibull functions. (a) Failure probability, survival probability and probability density functions varying with time; (b) Weibull failure probability varying with central temperature, temperature difference and heat flux.

Fig. 4. The comparison of three-parameter Weibull failure possibility functions of different kinds of glazing. (a) Comparison of temperature difference; (b) Comparison of total heat flux.

(a) The compartment model



(b) Distribution of TC and HF on fire-exposed surface

Fig. 1. The experimental setup and measurement instrument distribution.

(i) Crack initiation, 0.00 s

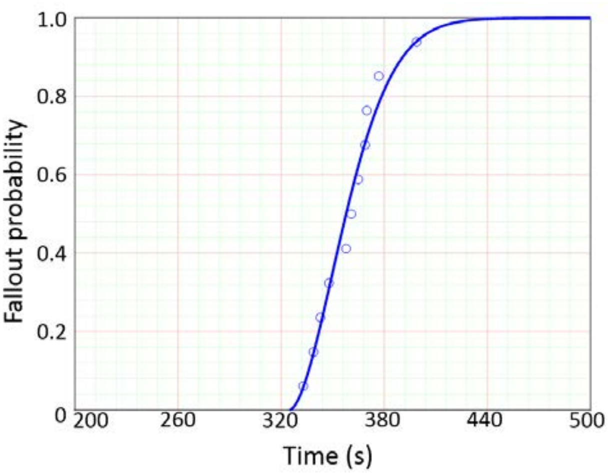
(ii) Glass falling out, 0.10 s

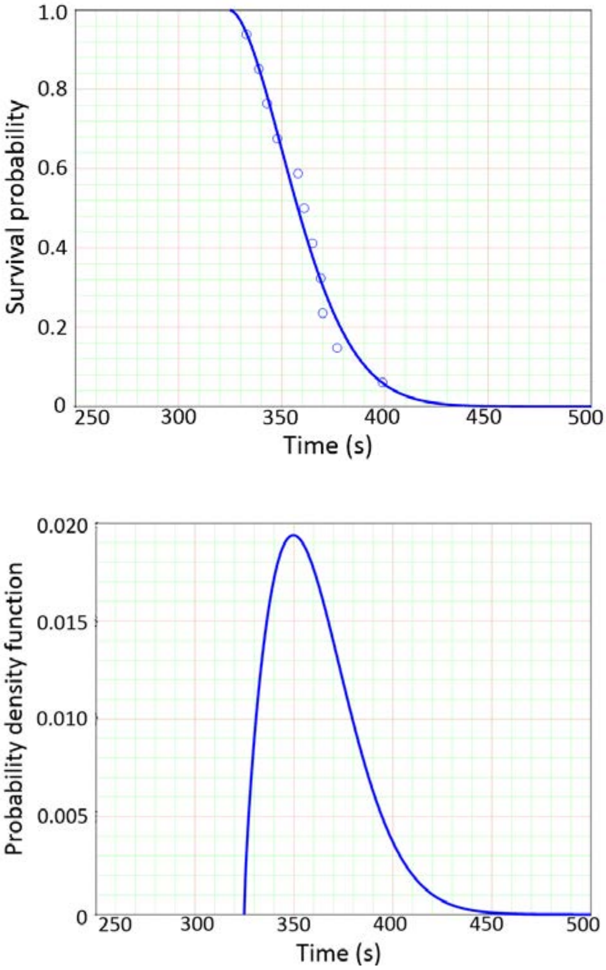

(iii) Complete fallout, 0.72 s

(a) The breakage and fallout process of tempered glazing

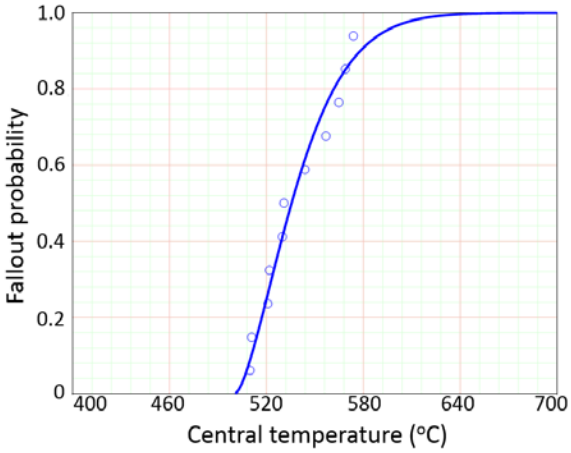
(b) The post crack path of tempered glazing

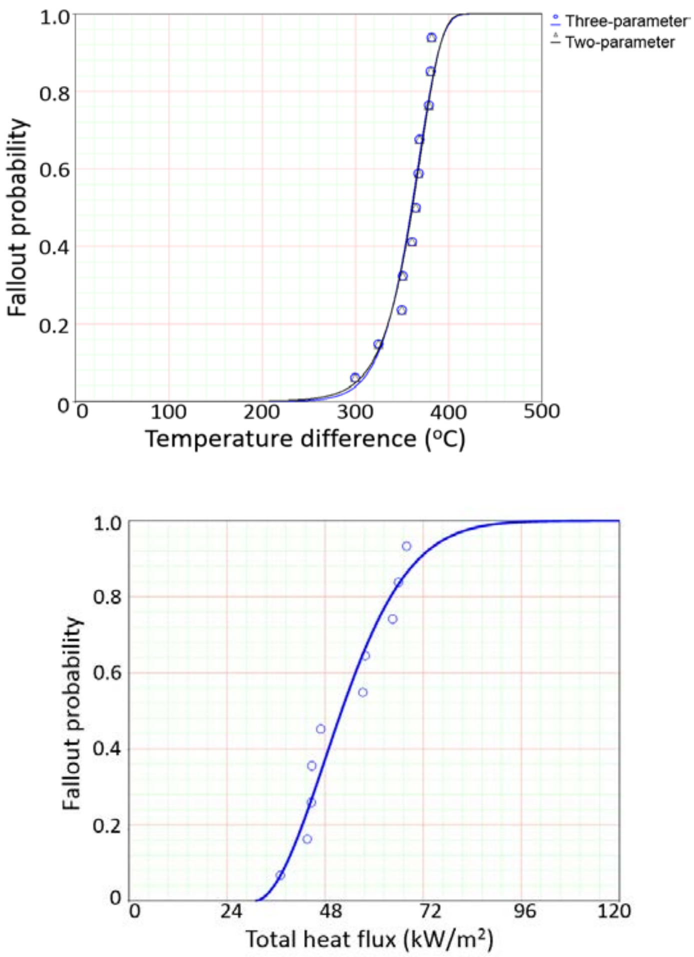
Fig. 2. The fallout behavior in Test 4.





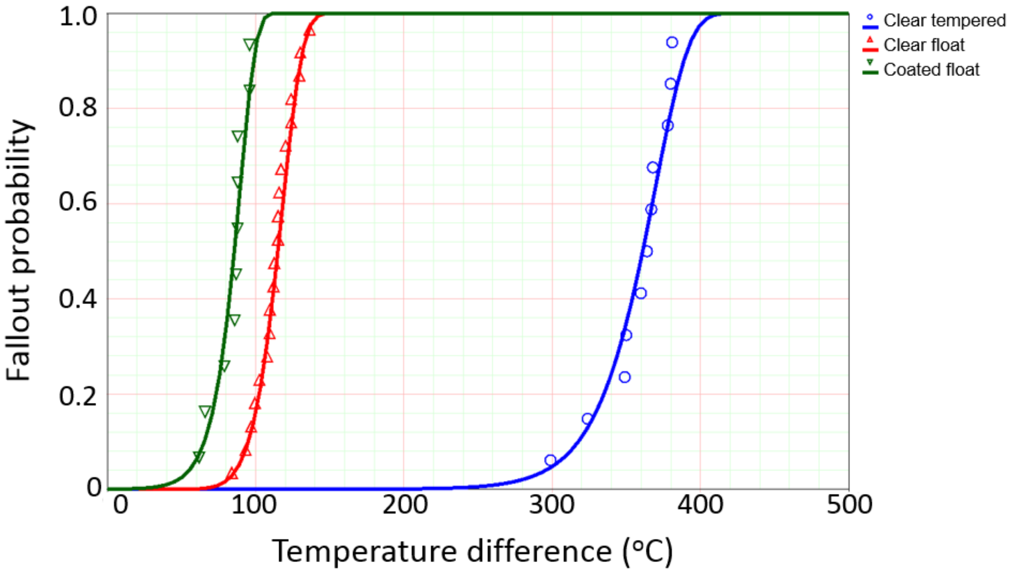
(a) Failure probability, survival probability and probability density functions varying with time



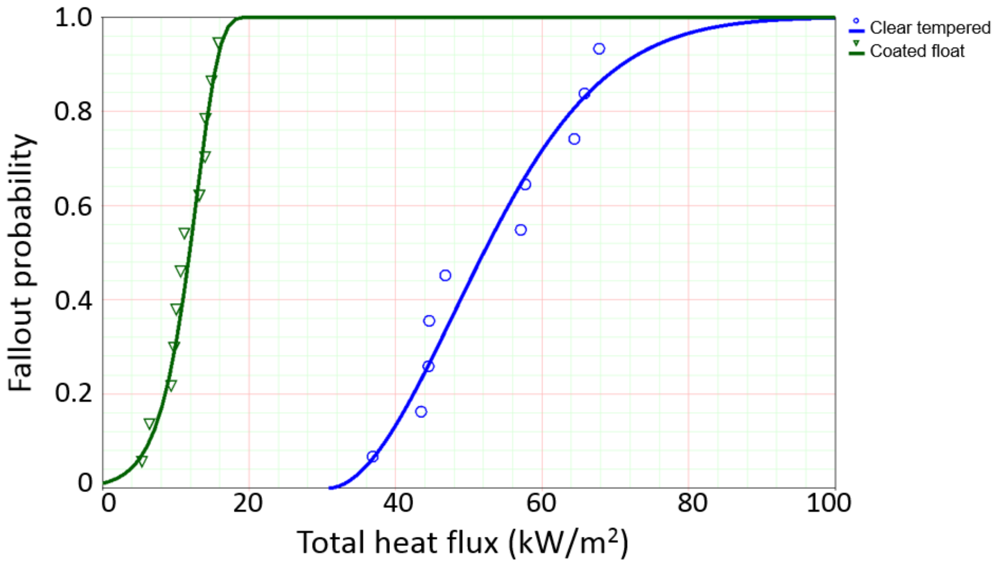


(b) Weibull failure probability varying with central temperature, temperature difference and heat flux.

Fig. 3. The curves of three-parameter Weibull functions.



(a) Comparison of temperature difference



(b) Comparison of total heat flux

Fig. 4. The comparison of three-parameter Weibull failure possibility functions of different kinds of glazing.